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GEOPHYSICAL INVESTIGATIONS AT PAHUTE MESA, NEVADA

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13. ABSTRACT (Maximum 200 words)

Part I of this study has concentrated on the assembly of a data base of geological and geophysical data for a transect at Pahute Mesa, Nevada. Existing data, in the form of well logs, gravity observations and seismic travel times, have been supplemented by new gravity and seismic data especially for the construction of a geophysical model of the shallow crust. The transect is modeled as an extensional basin, with up to 5 km of structural relief and volcanic fill. Major faulting is on the east side.

The second part of this study has applied the new GPS technology to geogetic monitoring of nuclear explosions at Pahute Mesa, Nevada. Significant deformation is observed to be caused by the test BULLION. New rapid survey methods have been successfully applied to perform studies, which would have been otherwise prohibitively time consuming.

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Contents

A Geophysical-Geological Transect at Pahute Mesa, Nevada

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Final Technical Report: Part I

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Introduction

The Pahute Mesa, Nevada, nuclear test site is situated atop a complex of volcanic centers. The youngest such caldera is the Silent Canyon caldera, about 14 Ma. It has long been recognized that a considerable thickness of volcanically derived material underlies this site (Orkild et al., 1968), but the details are obscured by a blanket of more recent tuffs from the Timber Mountain caldera, to the south. The structural development at Pahute Mesa has been controlled, over about the past 20 Ma, by successive, local volcanic activity and regional, basin and range extension (Byers et al., 1989; Warren, et al., 1985).

Spence (1974) recognized the presence of a major high velocity structure under the volcanic complex, that extends into the upper mantle. These results were based on travel time anomalies for telseismic P-waves from nuclear explosions at Pahute Mesa. The existence of some kind of deep high velocity anomaly has been confirmed in several studies since. Minster et al. (1981) used a much larger teleseismic data set and attempted to map structural variation in the crust and mantle beneath both Pahute Mesa and Yucca Flat. Taylor (1983) used regional propagation paths and teleseismic travel time residuals to build a similar, block-type model. In these later models the structure was parameterized by relatively thick layers ($\geq$ 5km), which were subdivided laterally into blocks of 10 km size or greater. The high velocity body begins at a depth in excess of 5 km; at shallower depths Pahute Mesa is characterized by low seismic velocities. Velocities up to 5% greater than expected for this region are to be found to depths greater than 100 km, in a zone which extends to the north and northeast of Pahute Mesa.

Although the resolution of these methods is quite low from a geologic standpoint, the existence and definition of spatially and azimuthally dependent anomalies in travel time and amplitude is very well established. The block type models mentioned above, as well as studies by Cormier (1987) and Lynnes and Lay (1988), have attempted to explain these anomalies using upper mantle structure. Cormier found that Taylor's (1983) velocity anomaly reproduced the amplitude anomaly very well in a qualitative sense, but only reduced the log-amplitude variance by 25%. A major limitation of the travel time residual models is a lack of adequate detail in the shallow (< 5 km) subsurface. This region is the scene of very large geophysical variations, involving low density and velocity volcanic materials filling a basin in a high-density, high-velocity basement comprised of Paleozoic sediments and Mesozoic intrusives. Amplitude anomalies at

Yucca Flat have been explained by Ferguson (1988) and McLaughlin et al. (1987) by using shallow crustal variation alone. While the structure at these two sites is very different, the shallow crustal structure at Pahute Mesa may be responsible for a least a portion of the amplitude anomaly in a manner not previously considered. The ability to predict seismic amplitude variations due to local structure is vital to the ability to accurately predict explosion yields in the context of a limited test ban treaty.

Local recordings of seismic signals from nuclear tests have also been studied. The principal focus of these studies has been the seismic source function (Stump and Johnson, 1984; Barker et al., 1991), but it has been necessary to develop one-dimensional velocity and density models for the computation of seismic Green's functions. A very good average velocity model, valid at very shallow (< 1 km) depths is to be found in Leonard and Johnson (1987), and a comparison of several one-dimensional models is made in Barker et al. (1991).

The availability of subsurface geologic and geophysical data is considerable and unique for a volcanic center. This data was developed to support the nuclear test activities and is restricted to depths less than the usual depths for test emplacement (i. e., about 600 m). Some older data extends to depths of a 1 km, but this is extremely limited. Recently, an increased effort has been made to synthesize the results of this subsurface exploration, starting with Warren et al. (1985). In the current study this data base will be extensively utilized to constrain the geophysical modeling. Figure 1 is an interpreted geologic cross-section for the transect shown on Figure 2.

The results considered here attempt to bridge the gap between the borehole data and the deep crust and upper mantle. A laterally variable model is constructed along a transect across Pahute Mesa, Rainier Mesa and extending to Yucca Flat. The geophysical constraints are provided by Bouguer gravity data and local P-wave travel times.

Gravity Data

The gravity map presented in Figure 2 is compiled from approximately 1500 gravity stations collected by the USGS, mostly in the 1960's (Healey, 1968) and about 250 more stations collected by the University of Texas at Dallas and Los Alamos National Laboratory (UTD/LANL) in 1985. The older data are sparsely sampled and predate both the existing road network and topographic maps. The elevations were usually controlled by altimeter. The accuracy of these older data may be only a few mGal.

The 1985 survey was conducted along roads spanning Pahute Mesa both east to west and north to south. Stations were spaced every 300 m, with position control provided by a Zeiss Elta-4 electronic distance meter. Two LaCoste & Romberg Model G gravity meters were employed. These data are conservatively estimated to be good to within 0.5 mGal.

Terrain corrections were calculated for the UTD/LANL gravity data using a special procedure in conjunction with hand-digitized elevation data from 1:24,000 topographic maps. Depending upon the local terrain, each 20 ft, 40 ft or 100 ft contour was digitized at arc intervals of 25 to 50 m.

The resulting irregularly distributed elevation data were then used in the following procedure. A multiquadric surface (Hardy, 1971) was fit to all data within 1500 m of each station. The number of data used in each case varied between about 350 and 1300. The terrain effect was integrated using a modification of Hammer's (1939) method. A total of 21 annular zones were defined, with radii from 5 to 1260 m. Within each zone, 24 approximately square compartments were specified. In each compartment the mean elevation was estimated from 20 pseudo-random samples of the multiquadric surface.

Additional terrain corrections out to a distance of 166.7 km were computed using a modified version of Plouff's (1977) program and the 30 arc-second regional topographic grid of mean elevations. Corrections for tides and meter drift were applied and a reduction density of 2000 kg/m^3 used. This relatively low density is justified by the resulting reduced correlation between gravity and topography.

The UTD/LANL data were merged with the older USGS data and points, which were determined to be outliers, were edited. The USGS data were already terrain-corrected; thus, new terrain corrections were not computed, but the USGS gravity data were reduced using the 2000 kg/m^3 density. Contours of the Bouguer gravity anomaly are shown in Figure 2. Differences in anomaly amplitude observed in this map as compared to earlier publications (e.g., Healey, 1968) are primarily due to the use of the lower reduction density, as opposed to the standard 2670 kg/m^3. The entire data set is described and included in the compilation of Harris et al. (1989).

Seismic Data

The seismic data used in this study are from a variety of sources. Travel time and waveform data from local recordings of nuclear explosions were gathered from the literature and were also acquired specifically for this study. We conducted a wide-angle seismic survey in 1986, using high explosive sources, in order to obtain information in the caldera margin area.

A joint program for the execution of a wide-angle seismic experiment was developed by the University of Texas at Dallas and Los Alamos National Laboratory in 1986. The Pahute Mesa geologic structure is laterally discontinuous, with several high impedance contrast layers, due to welded tuff and lavas (Orkild et al., 1968), and a high attenuation, with Q perhaps as low as 50 (Johnson, 1988). These facts discourage attempts to perform conventional reflection or refraction surveys. In Big Burn Valley, immediately southeast of Pahute Mesa, older volcanic rocks (Belted Range tuff) are exposed. These rocks are physically distinct from those which fill the Silent Canyon caldera. A shot point in Big Burn Valley permits the Silent Canyon structure to be "undershot", with seismic energy injected directly into layers corresponding to the deeper structure. Snyder and Carr (1984) and Hoffman and Mooney (1984) present the results of a similar survey at the Crater Flat caldera located 30 km to the south of Pahute Mesa. The success of the Crater Flat model indicated that a similar approach at Pahute Mesa might be fruitful. It is also difficult to obtain permission to drill shot holes on Pahute Mesa itself, due to the prevalence of archeological sites. The 1986 Pahute Mesa Seismic Experiment (PMSE86) was designed around these considerations.

A single shot point location was established in Big Burn Valley, and a line of recording stations was established along available roads trending northwest, roughly normal to the strike of the caldera margin and mapped faults. The line passes close to several important boreholes, particularly the deep holes PM-1 and Ue19w-1, which penetrate caldera margin structures. The survey geometry is shown in Figure 3. The recording line is 12.5 km long, with a 3.5 km near-offset from the shot point necessitated by topography. Twenty four- channel spreads of 1.5 km aperture and 67 m geophone group interval were deployed. Each channel recorded a string of 4.5 Hz vertical component geophones spaced 3 to 6 m apart. Fifteen bit, floating point records were made at a 2 ms sample rate.

Each spread recorded a shot from the Big Burn Valley shot point location, as well as a shot from each end with a

12 liter Dinoseis (ARCO trademark) gas exploder source. The explosive charges ranged from 13.6 to 680 kg, for near offsets ranging from 3.5 to 14.5 km. To provide redundancy, the spreads were overlapped by 50% for successive shots. The Dinoseis shots, equivalent to about a kilogram of explosive and vertically stacked over 4 to 8 shots, were not generally observable out to 1.5 km offset in the low Q, near-surface layers. These local shots were useful in establishing near-surface velocities for elevation static corrections on the recording line and near the shot point. The P-wave travel times for a total of 685 explosive records and 449 Dinoseis records were picked.

The nuclear tests Kernville (15 February 1988) and Alamo (7 July 1988) were recorded in order to provide ray paths with reverse propagation to PMSE86. Kernville, located just off the northwest end of the PMSE86 line, was almost perfectly sited to provide reverse coverage (Figure 3). Four event-triggered, 3-component recordings were made at stations KVA, KVC, KVF and KVG, using either accelerometers or seismometers. A fifth station failed to trigger and deployment of series of planned stations to the southeast was thwarted by scheduling difficulties. Alamo was located near the middle of the PMSE86 line (Figure 5) and was recorded at 3 stations in Big Burn Valley (ALA, ALC and ALD) and 1 on Rainier Mesa (ALE). Station ALB failed to record during the experiment. All the recordings of Alamo were 3-component seismometer records.

Waveform data for the nuclear events Scotch (23 May 1967), Boxcar (26 April 1968) and Almendro (6 June 1973) can be found in Perret (1976, 1983). These data are also presented in Barker et al. (1991). Additional travel times for Almendro were found in an Environmental Research Corporation report (Anon., 1974). Recordings of Farm (16 December 1978) are discussed in Stump and Johnson (1984) and travel times were provided by Brian Stump (personal communication).

Elevation static corrections were applied to reduce the receivers to a datum elevation of 1.9 km (the elevation of the PMSE86 shot point). Such corrections ranged up to several tenths of a second and may have velocity uncertainties of up to 50%, but the corrections seem to be reasonable as applied. Timing uncertainties in some of the nuclear explosion data are considerable and are of a similar magnitude in some cases. The travel times are range from 1-4 seconds, so that the travel time uncertainty is between about 3 and 10 percent.

The travel time data for PMSE86 were smoothed by the fitting of straight line segments by an outlier-resistant procedure (Velleman and Hoaglin, 1981). This reduced the number of travel time observations for PMSE86 to 11, which compares favorably to the 17 travel time observations from the 6 nuclear tests. Although these data are sparse, it should be noted that the shallow structure within the caldera is well constrained by boreholes. The seismic travel times, along with the gravity data, therefore provide important control on the deeper and laterally discontinuous structure at the caldera boundary.

Geophysical Modeling

The cross-section presented in this paper is controlled by the gravity observations, seismic wave travel times, and the subsurface geologic and geophysical data presented in the previous section. The interpretation of these data is based on forward modeling to match the observations from a common model parameterization, for rock type and associated mass density and compressional wave velocity. The cross section is very detailed in areas where well control is good and more generalized elsewhere.

The initial model was determined exclusively by geologic considerations and has been refined on the basis of the geophysical constraints. From 10-25 km on the cross section, well control is quite good down to 0.6 km depth and exists to about 1.5 km depth. Below 1.5 km, lithologies and properties are inferred from indirect geophysical measurements. The forward modeling, using known properties in the shallow (< 1.5 km) subsurface, is assumed to properly account for and "strip off" the shallow structure. Deeper horizons are then adjusted to produce a model fitting the geophysical data adequately. Where well control was nonexistent, some shallow areas were also adjusted. Such adjustments occurred primarily from 25-37 km on the cross-section.

The geologic cross-section was constructed from polygonal cross-section layers, with uniform, somewhat generalized lithologies. These lithologies were lumped together and identified on the basis of age, rock type and physical properties. A density function, either a constant or a linear function of depth, was assigned to each lithology. These smoothed density averages were usually determined from borehole gravity or density logs. With this type of pararmeterization, it is straightforward to calculate the gravity effect using the method of Murthy et al. (1979), for polygonal prisms of uniform cross section and infinite strike length. This assumption of two-dimensionality is acceptable for the chosen transect (Figure 2).

A regional gravity anomaly was estimated by low-pass filtering the gravity data in a 10 by 10 degree region centered on Pahute Mesa. The filter high cut was between 150 and 75 km wavelength. The low-pass-filtered regional grid was interpolated and subtracted from the observed Bouguer gravity values in a corridor 2 km wide containing the cross section. The residual Bouguer gravity data were modeled using relative densities above sea level and absolute densities below sea level. The use of data from a narrow zone along the assumed structural strike direction facilitates an understanding of the lack of two-dimensionality in the structure as evidenced by the scatter in Figure 4 of the observed values.

The seismic travel times for the model were originally calculated using the two-dimensional ray tracing method of Cerveny et al. (1977). Such modeling was rather unwieldy due to the differences in the model parameterizations required by the gravity and ray tracing computer codes. At each modeling uteration, we adjusted the model structure and tested against both the gravity and seismic observations. This process necessitated a 2 time-consuming reparameterizations of the model at each iteration. Other difficulties common to wide-offset raytrace modeling included critically refracted rays and the shooting of rays to emerge near specific points on the surface.

The calculation of travel times by finite difference solution of the eikonal equation developed by Vidale (1988) permitted a more flexible approach. The model parameterization was maintained on the polygonal basis with linear velocity versus depth functions in each polygon. To compute travel times for both critical and non-critical raypaths, the velocity distribution was rasterized to produce a dense grid of values for the finite difference code. Since only a single, easy-to-modify parameterization is required, new models can be constructed and tested quickly. The travel times computed in this manner may not be as accurate as is possible using the ray tracing method (see Qin et al., 1992), but they are thought to be sufficiently accurate for this purpose.

Displays of the two-dimensional density and velocity distributions (Figures 4 and 5), as well as vertical profiles (Figure 6) permit a visual inspection of the model. Manual, iterative adjustment of the polygon vertices and the density and velocity functions produced a sequence of models converging to an acceptable model shown as Figures 4, 5 and 6. Because this was a forward modeling effort only, the uniqueness and resolution of the model cannot be evaluated, but we believe that it is a reasonable and parsimonious representative of the possible models.

The fit of the model to the gravity data is characterized by a median absolute deviation (MAD) of 1.2 mGal. Although this is larger than the accuracy of the gravity data themselves, it should be contrasted with the scatter in the data due to structural variation along strike (and extremely shallow structure which is unaccounted for in the model. Variation from these sources is on the order of 3-4 mGal. The maximum deviation of 11.5 mGal is clearly due to three-dimensional structural effects. The two-dimensional model can be considered to represent the average structure in a 2 km-wide zone containing the cross-section. A less detailed model could be produced, which would fit the gravity data equally well, but would not reflect all the pertinent geologic information available.

The shot point and receiver locations are scattered in a much broader zone around the cross-section than the gravity data (Figure 3), but the travel times are somewhat less sensitive to the local variations. The velocity model that was fit is considerably less detailed than the density model. The travel times are fit with a MAD of 0.05 s, which is well within the uncertainties in the travel times, and the maximum deviation of 0.19 s is not unreasonable. Considerable latitude is possible in changes to this model, which will not significantly affect the fit to the observations.

Conclusions

The Bouguer gravity and sparse seismic travel time data have been useful in constructing a model of the 1-5 km deep structure under Pahute Mesa, Nevada. The use of known geologic structure for depths less than 1 km was essential in this process. The polygonal-basis modeling method used in this study has been very flexible. In the future, this forward modeling scheme will be incorporated with a nonlinear inversion method, for combined geophysical inversion of diverse geophysical data.

The new model indicates that the structure has more of the appearance of an asymmetrical graben than a classical caldera. This would be consistent with the hypothesis that the volcanic centers developed locally in a basin and range rift structure. Major structural relief on the pre-Tertiary surface, of 3-4 km, exists between Yucca Flat and Pahute Mesa. Most of this relief occurs in a zone between 25 and 30 km on the cross section (Figures 1, 4 and 5). This zone encompasses the Split Ridge, Scrugham Peak and Almendro faults. The proximity of explosion sources to similar fault-controlled structures at Yucca Flat, has been demonstrated to cause major seismic amplitude anomalies (Ferguson, 1988). The effect of the structure modeled here on seismic amplitudes needs further investigation.

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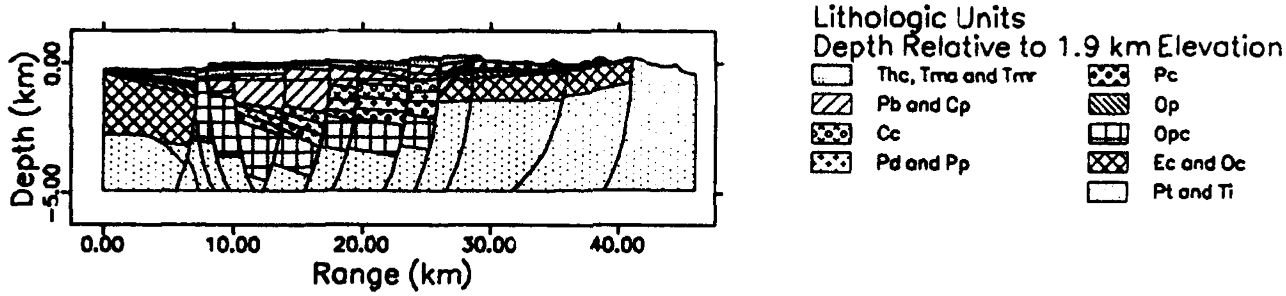

Figure 1. Generalized geologic cross section for the transect at Pahute Mesa, Nevada shown in Figure 2. Thc, Tma and Tmr are units from the Black Mountain and Timber Mountain volcanic centers. Pt and Ti are Paleozoic sedimentary and Tertiary intrusive rocks. The Pc is associated with the collapse of the Silent Canyon caldera.

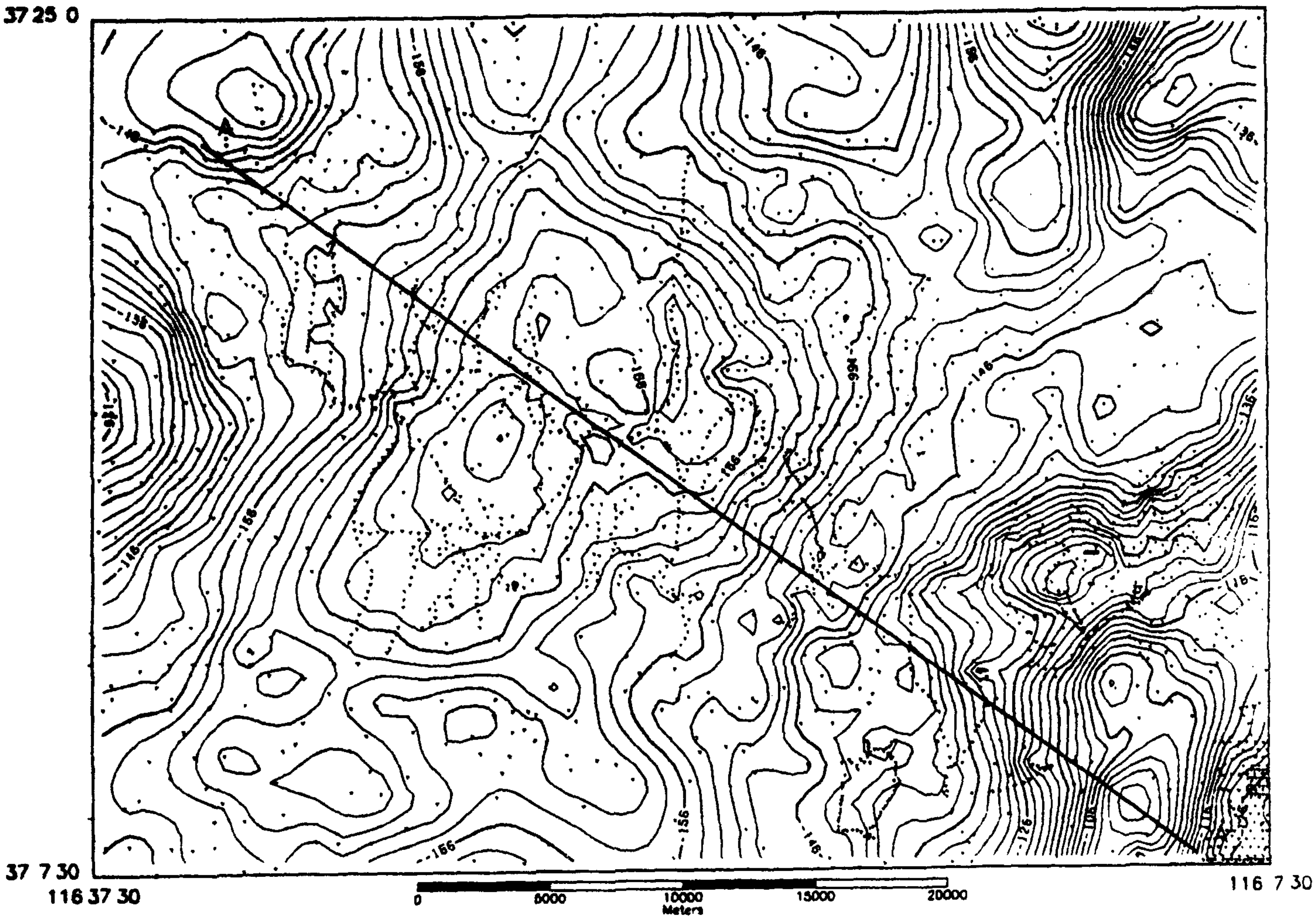

Figure 2. Bouguer gravity (reduced at 2000 kg/m^3) anomaly map for Pahute Mesa, Nevada. The contour interval is 2 mGal. The location of the geophysical transect is delimited by A to A'.

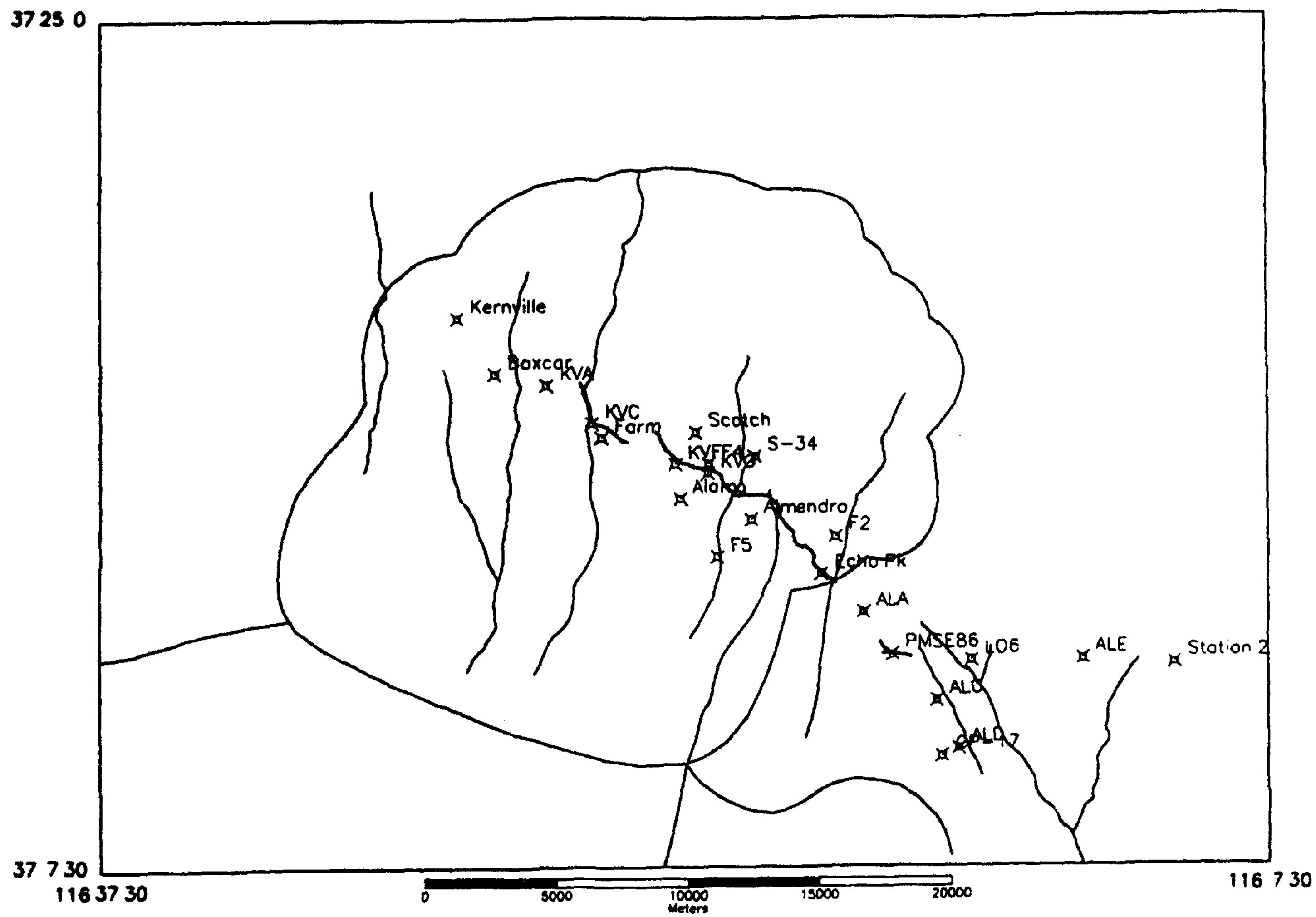

Figure 3. Locations of seismic shot points and receiver stations at Pahute Mesa, Nevada. The receivers for PMSE86 are shown by the small X's. The outline of the Silent Canyon caldera and major north-south trending faults are shown for reference.

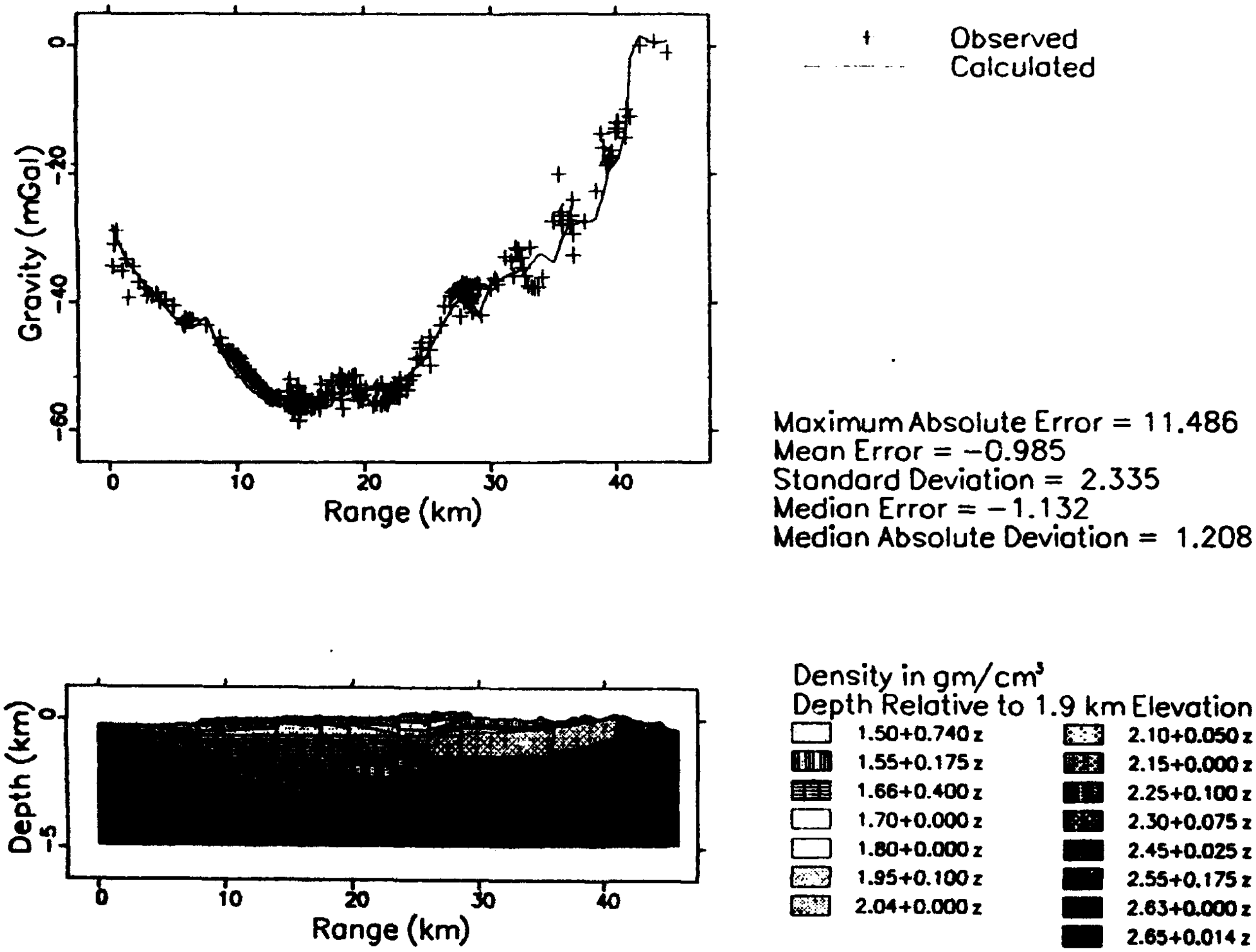

Figure 4. A profile of the observed gravity data, with 2 km of the transect in Figure 2 (+'s) and the anomaly calculated from the density distribution in the cross section below.

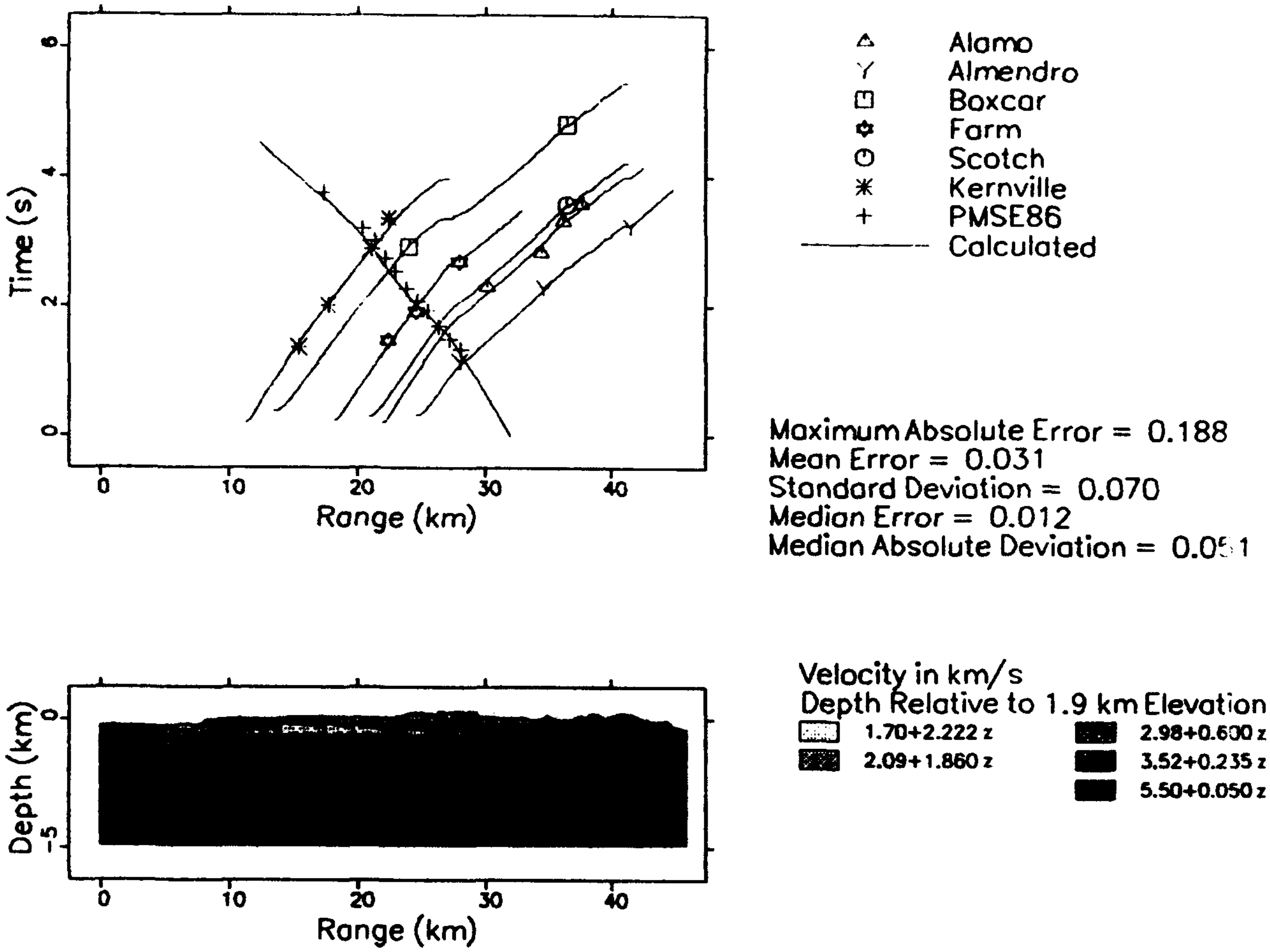

Figure 5. The observed P-wave travel times for the shots and receivers in Figure 3 and the computed travel time curves for the velocity distribution in the cross section below.

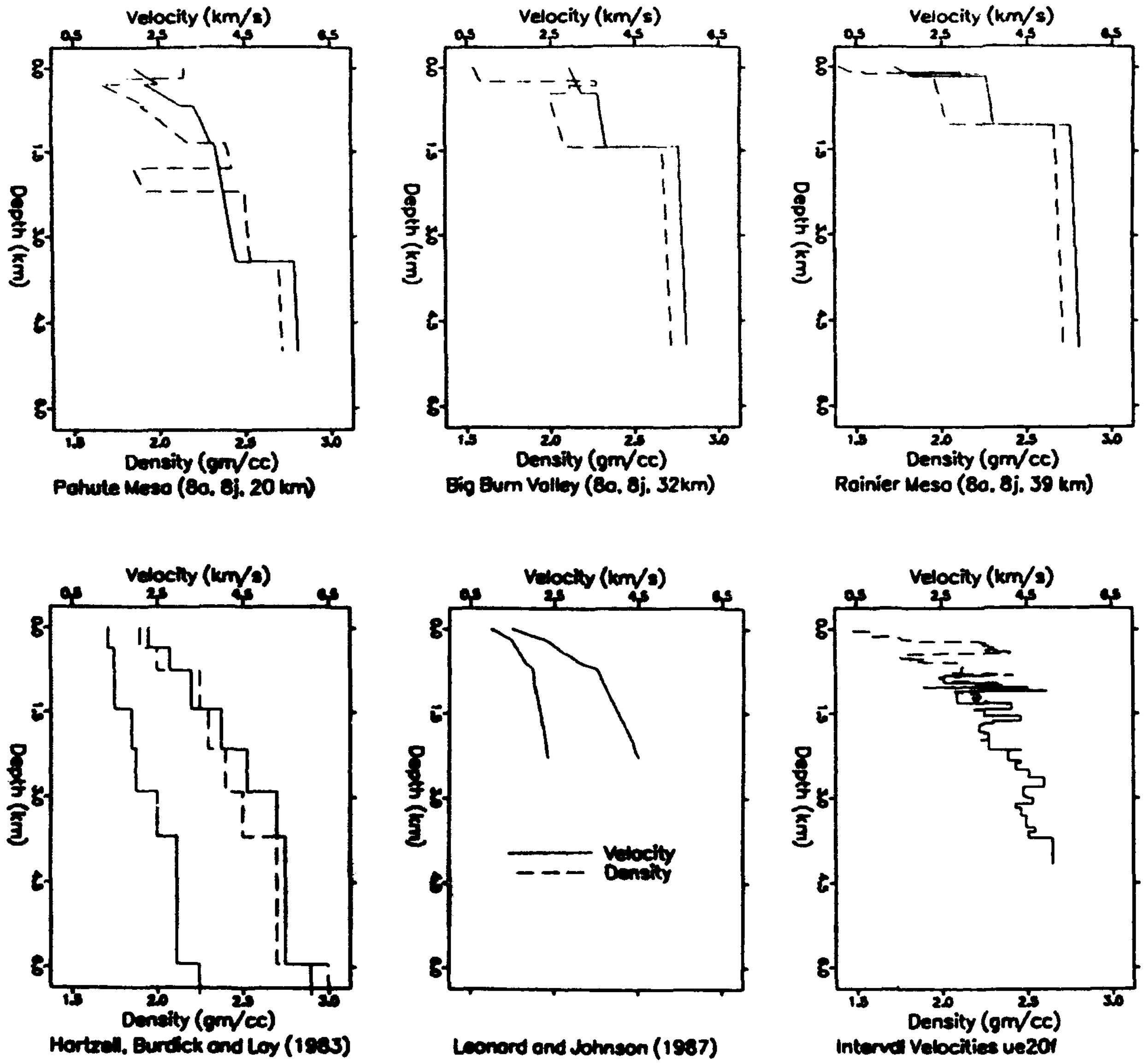

Figure 6. Vertical profiles of velocity and density from the model in Figures 4 and 5. P- and S-wave velocity and density relations for Pahute Mesa, Nevada from the seismological literature are on the bottom row, along with logs from a deep well, ue20f, which is south of the western portion of the transect.

Geodetic Experiments on Nevada Test Site Events Using the Global Positioning System

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Final Technical Report: Part II

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Introduction

Underground nuclear explosions produce considerable deformation in their vicinity. Patterns of dilatation due to cavity formation, fracturing and subsidence due to cavity collapse, as well as motion on pre-existing faults are regularly observed. Geodetic studies of this deformation have been made on several occasions in the past 30 years, including Dickey (1969; 1971), Savage et al. (1974) and Krier et al. (1987). In addition to strong motion seismograms, post-shot fracture mapping and aftershock seismicity, geodetic studies provide important constraints on the nature of explosion induced deformation, which may be due to tectonic release or block motion (Massey, 1981). In some respects, nuclear testing provides a natural laboratory for the study of fault mechanics.

This report will discuss two new surveys made for the events BULLION (13 June 1990) and BEXAR (4 April 1991). The locations of these events are shown in Figure 1. Geodetic measurements for these events were made using the new Global Positioning System (GPS) satellite navigation technology. These experiments were intended to demonstrate the efficacy and efficiency of rapid GPS survey methodology in Earth deformation studies.

Explosion Mechanics

The phenomena associated with a contained, underground explosion are summarized below. The scaled depth of burial is

$$d_s = d \,/\, W^{1/3},$$

where yield, W, is given in kilotons (kt). Houser (1969) states that for scale depths greater than about 60 $m/kt^{1/3}$, no excavated crater is formed and for $d_s > 90$ $m/kt^{1/3}$, the explosion is effectively contained, for conditions at Yucca Flat, Nevada (overburden density of between 1800 and 2100 kg/m^3).

Immediately following the detonation, a spherical cavity is formed, with radius proportional to $W^{1/3}$. Mueller and Murphy (1971) provide the relationship,

$$r_c = 28.0\ W^{0.29}\ d^{-0.11},$$

with depth and radius in meters. Intense fracturing occurs around the cavity, with an inner crushed zone tapering into a radial fracture pattern. Fracture opening is limited by the build-up of hoop stresses caused by the compression wave radiating from the explosion. Borg (1973) indicates that the radius of pervasive fracturing is between 2.7 to 3.5 r_c. Thrust faults may be formed in a conical zone (45° dip) above the cavity by the outgoing compressional wave. Evidence of this thrusting is found in moment tensor solutions for several explosions (Massey,1981).

The compression wave, when reflected from the free surface, produces a tensile failure at depth. A slab of material is separted and propelled in free fall, from whence it subsequently "slaps down". This spall phenomena extends to a radius of one or two depths of burial around the epicenter. There may be more than one spalled slab and the spall zone may not be cylindrically symmetric due to local structural weakness.

After the event, there may be a net doming over the shot point due to the dilation associated with the fracturing. This may be very short lived due to the instability of the cavity at depth. For explosions above a certain scale depth, approximately 300 $m/kt^{1/3}$ at Yucca Flat, Nevada, (Houser, 1969), the cavity will collapse and the void will migrate upward. If collapse extends to the surface, a collapse crater, with a volume similar to the original cavity, will remain. Collapse craters are the rule at Yucca Flat, in alluvium, but are rare at Pahute Mesa, with more competinent volcanic rocks at the surface. In either event, there may be a resulting net subsidence over the shot point.

In addition to the tension cracks formed by the explosion, pre-existing, natural fractures, either joints or faults, may be activated. New fracture patterns are often closely associated with existing fractures (Barosh, 1968 and Bucknam, 1969). Modest size blocks of rock may respond passively to the explosion (i. e. they are simply pushed around) or regional tectonic strain may be released (i. e. an earthquake is triggered). Considerable controversy has surrounded the tectonic release hypothesis and geodetic measurements may have some bearing on the resolution of the debate (Massey, 1981).

Dickey (1969) observed that explosions within 300 $W^{1/3}$ m of the Yucca fault would initiate fault displacement. Rupture seems to only occur within the spall zone (Weaver, personal communication). At Pahute Mesa the empirical relationship between fault length and yield or magnitude was investigated by McKeown and Dickey (1969). The SCOTCH test in 1969 had a body wave magnitude of 5.7 (PDE) and a yield of 155 kt, just above the current treaty limit of 150 kt. This event ruptured the U19as fault (later termed the Scotch fault) for about 1.5 km. This could be taken to an upper limit of rupture to be expected from the BULLION and BEXAR events. The post-shot fracture map for BULLION shows rupture on the West Greeley fault over a total distance of 2.7 km in several discontinous segments, however the distance from the explosion hypocenter to the fault is only about 0.5 km.

Previous Geodetic Studies

Early applications of geodetic methods were to the large, megaton scale explosions BENHAM (Dickey, 1969), JORUM (Dickey, 1971) and HANDLEY (Savage et al., 1974) at Pahute Mesa, Nevada. In Dickey's work quadralateral strain figures, one or two kilometers across were deployed within 18 km of the explosion epicenter using electronic distance measuring instruments. The horizontal components of strain were computed from displacements within these figures. Attempts were made to resolve the strain into contributions due to cavity expansion and dislocations on known faults. During BENHAM , a level line was run through the epicentral region, which demonstrated a general subsidence of up to 0.76 m, with differential motion on faults of up to 0.5 m.

During the JORUM experiment a 2 km line, located about 10 km southwest of the epicenter, was monitored continuously for 5 days, starting 5.5 hours after the test. Several steps in displacement were recorded, one of which seemed to be associated with an aftershock of magnitude 2.25.

The HANDLEY survey (Savage et al., 1974) was performed on a much larger scale. A network of seven stations and seventeen baselines was established, with a 30 km aperture enclosing the test location. All baselines were measured with a Geodolite. Atmospheric measurements were simultaneously made from aircraft in order to correct for refraction effects. Five repeat surveys were made starting two weeks after the test, with the last made three years later. A relaxation of baseline lengths was observed within two years of the test. Initial changes of up to -247 mm, underwent some reductions and even reversals. Massey (1981) has used this as evidence against the tectonic release hypothesis, suggesting that the pre-shot fault configuration had long term stability.

A more recent examples of geodetic surveys are found in Krier et al. (1987). Two Yucca Flat explosions, KINIBITO and GLENCOE were surveyed prior to and after the tests. In both cases dense lines of stations were established perpendicular to the strike of nearby faults (generally north-south), north, south and east (the fault side) of the explosion epicenter. Horizontal displacements were determined by electronic distance meter and elevations were determined by leveling. Strike-slip motion on the faults was evident, as well as vertical displacements. A general radial, outward displacement was also observed. Differential compaction of alluvium, in a surface layer which thickens across the faults, was thought to be responsible for much of the vertical displacement.

GPS Methodology

The Global Positioning System is the latest and best of a series of satellite based navigation systems deployed by the Department of Defense. Details of the operation of the system may be found in Lambeck (1988) and Leick (1990). A good summary is contained in Dixon (1991) and an even briefer summary will be presented here. A constellation of satellites orbits the Earth at 20,000 km altitude, in six orbital planes. At least eight of the satellites will be visible to an observer on the surface at any time, although the incomplete constellation at the time of the surveys presented here did not provide this kind of 24 hour coverage. A GPS receiver contains a clock, as do all of the satellites. Positioning is achieved by synchronization of the clocks through signals broadcast by the satellites. The ranges to the satellites are determined by the travel times of the radio waves, since the satellite positions are known through ephemeris data broadcast by the satellites. These positions are accurate to tens of meters, however the coded military signals provide positions which are about ten times better, but neither are sufficient for geodetic purposes.

Highly accurate relative positions are achieved by comparing the signal phase between two receivers during post-processing of recorded tracking data (double difference carrier phase processing). The linear equations which determine the position from the travel times are differenced between receivers and satellites (double difference) and the new equations solved for relative position from the phase differences. One or more receivers are set up at known, base locations and one or more receivers can rove between points to be determined. The use of phase differences results in an ambiquity in the roving receiver's position due to the unknown number of cycles or wavelengths present for each satellite. At any observation epoch, hundreds of wavefront intersection points will lie within a few meters of the true position, one of which is correct. The problem is to resolve this ambiquity through redundant measurements of some kind.

Once the correct solution is found, baselines can be measured to within centimeters and even milimeters over distances of thousands of kilometers. Elevations are less well determined, because satellites below the receiver are not visble, but even so, centimeter accuracy is possible. The GPS system actually has set new standards for survey performance, when compared to conventional optical methods. The previous higest grade of survey, termed first order first class, three new GPS based levels exist above, now called B, A and AA (FGCC, 1989). Advantages also accrue from the necessity for vertical rather than horizontal visiblity and the fact that measurement errors do not accumulate within a network of stations, each measurement being independent (although changes in the satellite configuration determine the precision). Errors due to ionospheric dispersion are correctable by the use of a dual frequency system. All satellites broadcast simultaneously on the L1 (1575.42 MHz) and L2 (1227.60 MHz) channels. Errors due to the lower, neutral atmosphere (troposphere) are probably not too important for the short (< 10 km) baselines involved in these experiments.

Several modes of data acquisition are possible. The most widely used to date has been the static mode. Recordings are made for extended periods of time, at the base and unknown locations, while both receivers remain stationary. For baselines of a few kilometers the recording time may be tens of minutes, but for long baselines of hundreds of kilometers the recording time may be hours. While this method is very effective, it is also very slow. In this study we endeavored to employ two more rapid techniques.

The kinematic method depends on the receiver maintaining continuous lock on the satellite signals, while it is moved from place to place. A brief pause (30 to 120 s) at each monument to be positioned is all that is required, as the receiver position is continuously maintained in transit. The survey is initialized on a known, short baseline, often through a swapping of the antennas on the base and roving receivers. Another approach, used in this study, was to establish a station by the static method, which is then used as a known baseline to initialize the signal phase. Any station known to within 5 cm could be used for this purpose. It is difficult in practice to maintain lock on at least four satellites, due to the fact that the high frequency radio signals are easily blocked by topography, trees, buildings, vehicles and people (Balde et al., 1992).

The dual occupation, rapid static method (Mader, 1992; Ziegler, 1992) seems to be the most satisfactory of the techniques, in that occupation times are brief and continuous signal lock is not required. In this method each monument is visited twice, at least 45 minutes between visits, so that the satellite configuration will have changed. A systematic search of the so called ambiquity function, permits the resolution of the integer phase ambiquity at each station (Mader, 1992 and Talbot, 1991). The BULLION survey utilized both the kinematic and rapid static methods, although rapid static type data was acquired at all stations. The BEXAR survey was based entirely on the rapid static method. Some static solutions were employed for base station ties to external monuments in both surveys.

Baselines were generally much less than 10 km and thus presented few difficulties with atmospheric related errors. Dual frequency receivers were used at all times, so that corrections for ionospheric dispersion could be made, if necessary. All solutions reported here are L1 only, except for the statically detrmined baseline between stations STAR and 20, in the BULLION survey. Errors involving deficiencies in the satellite configuration were reduced by a careful choice of the time window for data collection. The dilution of precision is monitored continuously in the receiver and whenever limits were exceeded, surveying was discontinued until the values improved. This would usually entail a wait of up to an hour or so, until the satellite configuration would again be satifactory. During 1990 and 1991 the satellite constellation was incomplete, so that only a limited time window of 8 to 10 hours per day was available, often at night.

The monuments surveyed were temporarily established, especially for these projects, with the exception of a few permanent monuments of long standing. The permanent monuments are maintained by Holmes and Narver, Inc., for operations at NTS. Where possible a brass cap was bonded to rock outcrop with silicone cement. In the BULLION survey, small wooden hubs, with a punched nail inset, were emplaced in soil covered areas. In the BEXAR survey, lengths of steel reinforcing rod were driven into soil covered areas and topped with a marked plastic cap. All of these monuments were apparently quite stable over the short period of two or three months between repeat surveys.

Structural Setting

Pahute Mesa, Nevada is located at the site of a complex volcanic center, with several collapse features buried under a blanket of younger tuffs from the Timber and Black Mountain volcanic centers (Orkild et al. 1968). These features are further dissected by Basin and Range extension along north-south trending faults, which creates an asymmetrical (deeper on the west) graben structure (Warren et al., 1985). East-west trending structures have been recognized at Pahute Mesa as well (Warren, personal communication). These appear to be related to the buried caldera structures and result in abrupt changes in the thickness of units within the fill and the truncation of north-south trending faults. Although these so called shear zones have been active until the most recent units were emplaced, they do not result in mappable fault traces, perhaps due to the unfavorable orientation of the current stress field.

While the north-south faults almost always localize deformation during the nuclear tests, there is evidence that the east-west trending shear zones respond as well. Fractures do not open along the shear zones, but compressional features do form. These have been termed pressure ridges and often firm en echelon patterns along the trend of the shear zones. Figure 2, adapted from Maldonado (1977), shows postshot fracture maps from FONTINA (m_b 6.3) and MUENSTER (m_b 6.2). The FONTINA test, located about 6 km west and 1 km north of BULLION, shows pressure ridges on the trend of the East Thirsty Canyon shear zone. MUENSTER is about 2.5 km due west of BEXAR and produced pressure ridges on the northwest-southeast trending Silent Canyon shear zone.

The BULLION test was located near the deepest portion of the volcanic fill and only half a kilometer west of a major Basin and Range fault, the West Greeley fault. Another, similar but more minor fault is located about the same distance to the west (Figure 3). Both faults dip to the west at a high angle. The BULLION working point was just below the water table at a depth of 687 m.

Nuclear tests in the vicinity of BULLION are displayed in Figure 4, with body wave magnitudes and names plotted. The West Greeley fault, just to the east of BULLION, has been activated by numerous tests in the past. The 825 kiloton test GREELEY ruptured 6 kilometers of the fault on 20 December 1966. This previous history of testing may have a substantial effect on motion during subsequent events.

Results of the BULLION Survey

The 31 stations shown in Figure 3, were occupied both pre- and post-BULLION in June and July of 1990. STAR and CROW are permanent monuments with conventionally surveyed locations. Stations 15 (not shown) and 24 were also occupied by accelerometers during the test. Vertical displacement profiles have been constructed along lines 1, 2 and 3.

A total of 32 stations were successfully positioned in the BULLION survey. In the before and after the event surveys we then have 64 total solutions, of these 40 were solved at least two times. These repeat measurements form the basis for an analysis of the reliability of the solutions. Final values for the displacement estimates were formed by taking simple averages of the repeated measurements. The absolute values of the maximum coordinate differences were used in the repeatability analysis. Rank order statistics were then applied to characterize the error distribution. The results are summarized in Table I. Vertical spread refers to the maximum absolute elevation error, horisontal spread refers to the vector magnitude of the horsontal coordinate maximum absolute differences and total spread is the vector magnitude of all three coordinate maximum, absolute differences.

The results in Table I indicate that the error distribution is skewed to the high side. While 50% of the vertical and horizontal repetitions are less than 1.5 cm apart, 75% are less than 2.5 cm apart, but errors range up to 6 cm. It cam be assummed, for the purposes of this study, that displacements in Figures 5 and 6 greater than about 3 or 4 cm represent a true geophysical signal. A similar analysis of the stations monumented with wooden hubs versus those stations with brass caps bonded to rock, indicates that the brass caps are somewhat more stable. If all stations had been founded on rock the error might have been reduced by about 1 or 2 cm. Due to the limited nature of the repeatablity test and the fact that solutions were obtained by two different analysts (D. G. Z. and C. L. V. A.), with two different computer codes (the National Geodetic Survey's Omni and Trimble Navigation's Trimvec) and two different methods (kinematic and rapid static) variously applied at each station, it is best not to put too much stress on this analysis. It is apparent, however, that usable geophysical measurements were obtained.

Scaled, horizontal displacement vectors, due to the nuclear test *BULLION* are plotted in Figure 5. These horizontal components of motion are generally much larger than the observed vertical displacements. Although motion is observed that is consistent with right-lateral movement on the West Greeley fault (500 m east of BULLION), the predominant transport in the northern part of the map is to the west. This motion is consistant with left-lateral motion on the East Thirsty Canyon shear zone. This conclusion is well supported by the data and is quite surprising. Transport toward ground zero is also somewhat unexpected and may be related to observed subsidence.

The vertical displacements due to the nuclear test BULLION have been profiled in Figure 6. The pattern shown on these profiles is rather complicated and not well represented by the sampling scheme employed. Line 1 is normal to the mapped structure, but parallel to the suspected East Thirsty Canyon shear zone. Lines 2 and 3 are both parallel, and very close, to mapped faults. Significant displacements are observed in both an absolute and a relative sense. In line 1 subsidence is observed between normal faults north of ground zero. Up and down motion, with a wavelength of approximately 1.5 kilometers, is observed on normal faults on the east and west of ground zero. Station 13 appears to be an outlier, distinct from the pattern. Stations 16 and 33, with more significantly anomalous behavior (vertical displacement of -43 cm at station 16 and horizontal displacement of 55 cm at station 33) were editted from these results. These two stations are located on the steep hillside, adjacent to the West Greeley fault and seem to have been involved in a slumping phenomena.

The BEXAR Survey

The nuclear test BEXAR was executed on 4 April 1991, prior to the test in February and after the test in May, the network displayed in Figure 7 was surveyed. Most of the locations in this network were also occupied by accelerometers or seismometers during the test. The design of this survey was influenced by several perceived limitations in the BULLION survey. The overall aperture of the network is greater, about 10 km as opposed to 3 km. The stations are more randomly distributed, although a rough north-south and two east-west lines may be drawn through the stations. In compromise, the sample density is much less, even on the transect lines.

During the surveys two base stations were occupied at all times, so that a greater strength and redundancy results. It will be possible to perform a meaningful least squares network adjustment on these data. All stations were occupied at least twice, during each survey. All processing of these data will be by the ambiquity function method (Mader, 1992). No attempt was made to maintain signal lock for kinematic processing. The network was tied to a station located well outside of the expected deformation, about 20 km to the south. Three permanent monuments were included in the network.

The results of this survey are not yet available, but it is expected to be as successful as the BULLION survey and possibly more informative. The data will be examined for deformation along the Silent Canyon shear zone, as well as on the mapped north-south trending faults.

Conclusions

The utility of GPS positioning, in rapid static and kinematic modes has been demonstrated. It is possible to obtain data from networks of around 50 stations, with an aperture of 10 km, in several days of effort.

Significant displacement vectors were obtained in the BULLION survey. Horizontal motions of up to 20 cm and vertical motions of up to 10 cm were observed. Resolution was found to be on the order of a few cm. Deformation was observed along known faults and unexpectedly along the East Thirsty Canyon shear zone. The limited spacial coverage of these data have somewhat limited the interpretation, but the results do prove the effectiveness of the methods employed.

These surveys are the first earth deformation studies to employ the rapid static method. The results obtained have verified the confidence placed in the methods. The possiblity of performing more rapid surveys, on both nuclear tests and in post-earthquake studies, is now open. It would be of particular interest to utilize the rapid survey methods to repeatedly survey certain monuments in the post-event phase to look for time dependent effects.

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Table I

Spread	Minimum	1st Quartile	Median	3rd Quartile	Maximum
Vertical	0	3	10	21	41
Horizontal	4	9	14	25	59
Total	5	11	18	30	67

Units are millimeters

Total of 40 points

Table I. Rank order statistics for the maximum coordinate differences among the repeated stations of the BULLION survey.

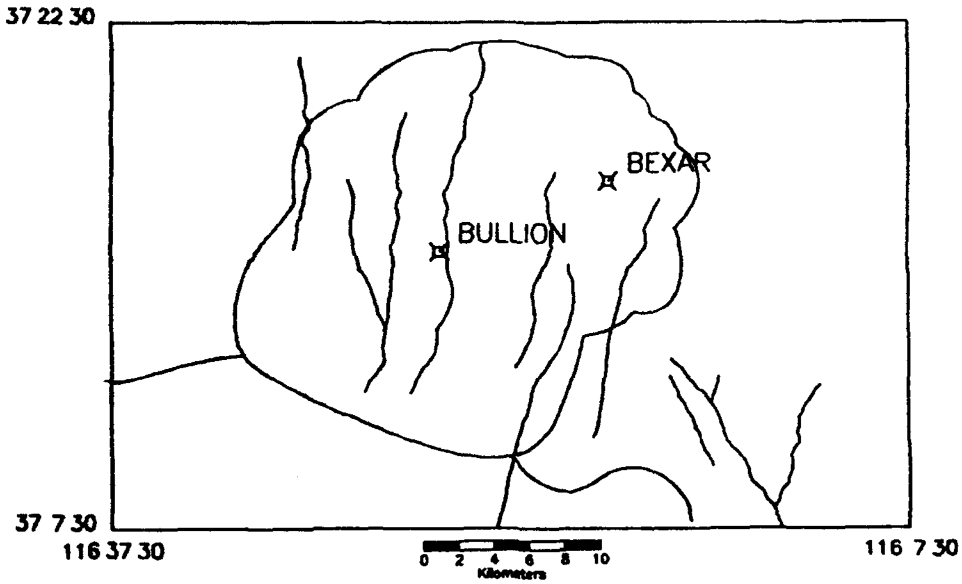

Figure 1. Location of the nuclear tests BULLION and BEXAR. The outline of the Silent Canyon caldera and the major north-south trending faults are shown for reference.

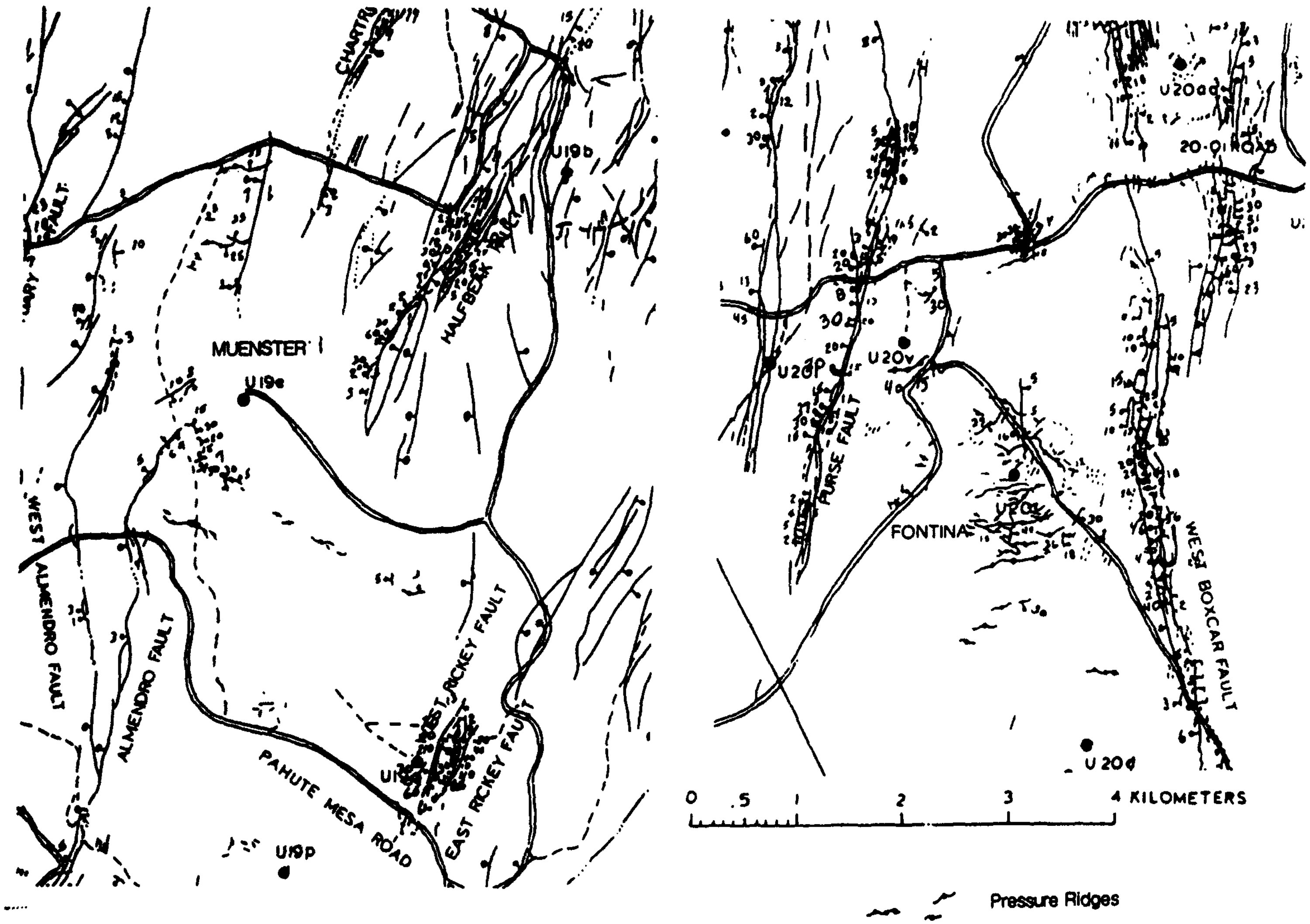

Figure 2. Post-event fracture maps for the tests FONTINA on the right and MUENSTER on the left (after Maldonado, 1977).

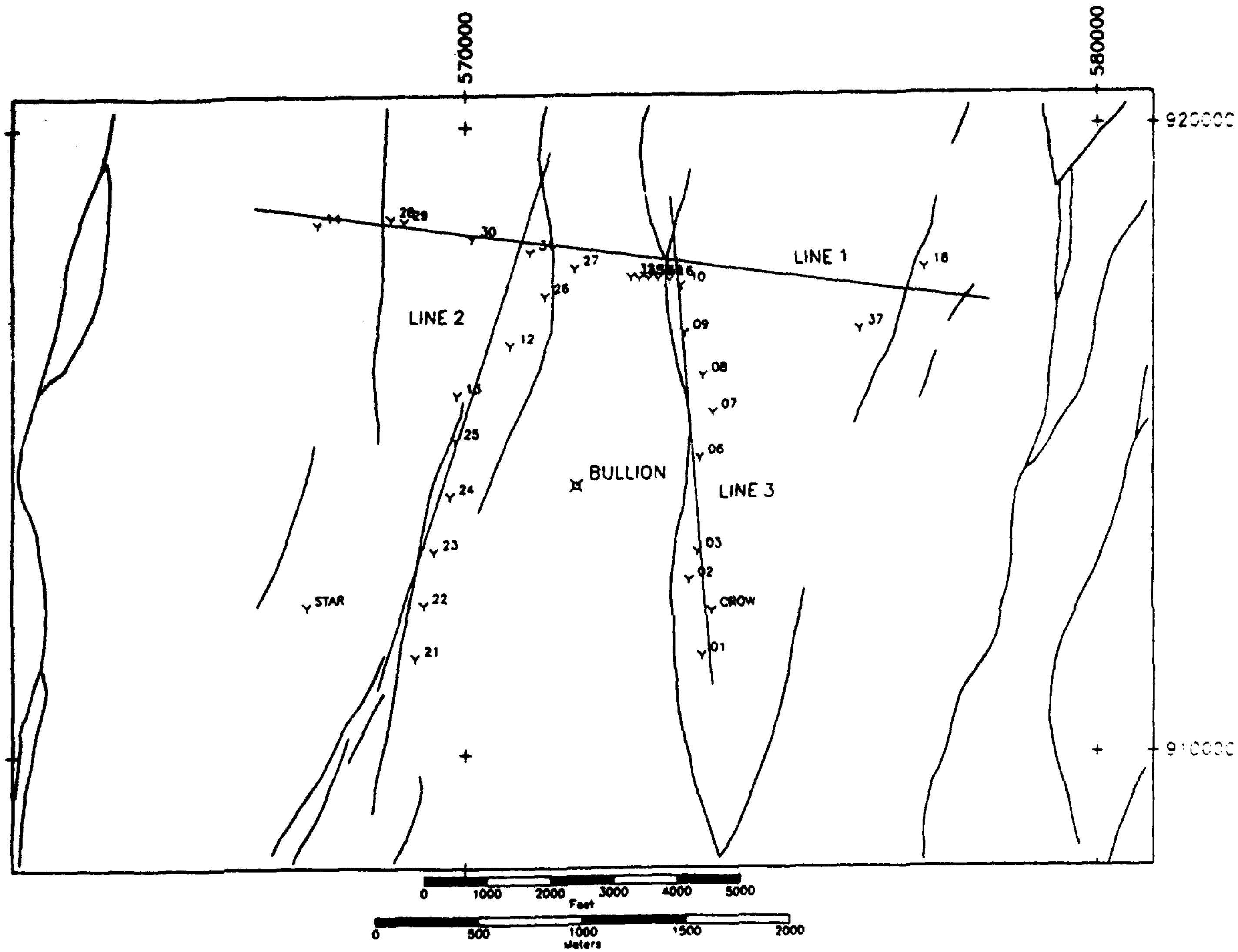

Figure 3. The network of monuments established for the BULLION survey. Faults which have been mapped in the vicinity are also shown on the figure. Lines 1, 2 and 3 are used for vertical displacement profiles in Figure 6.

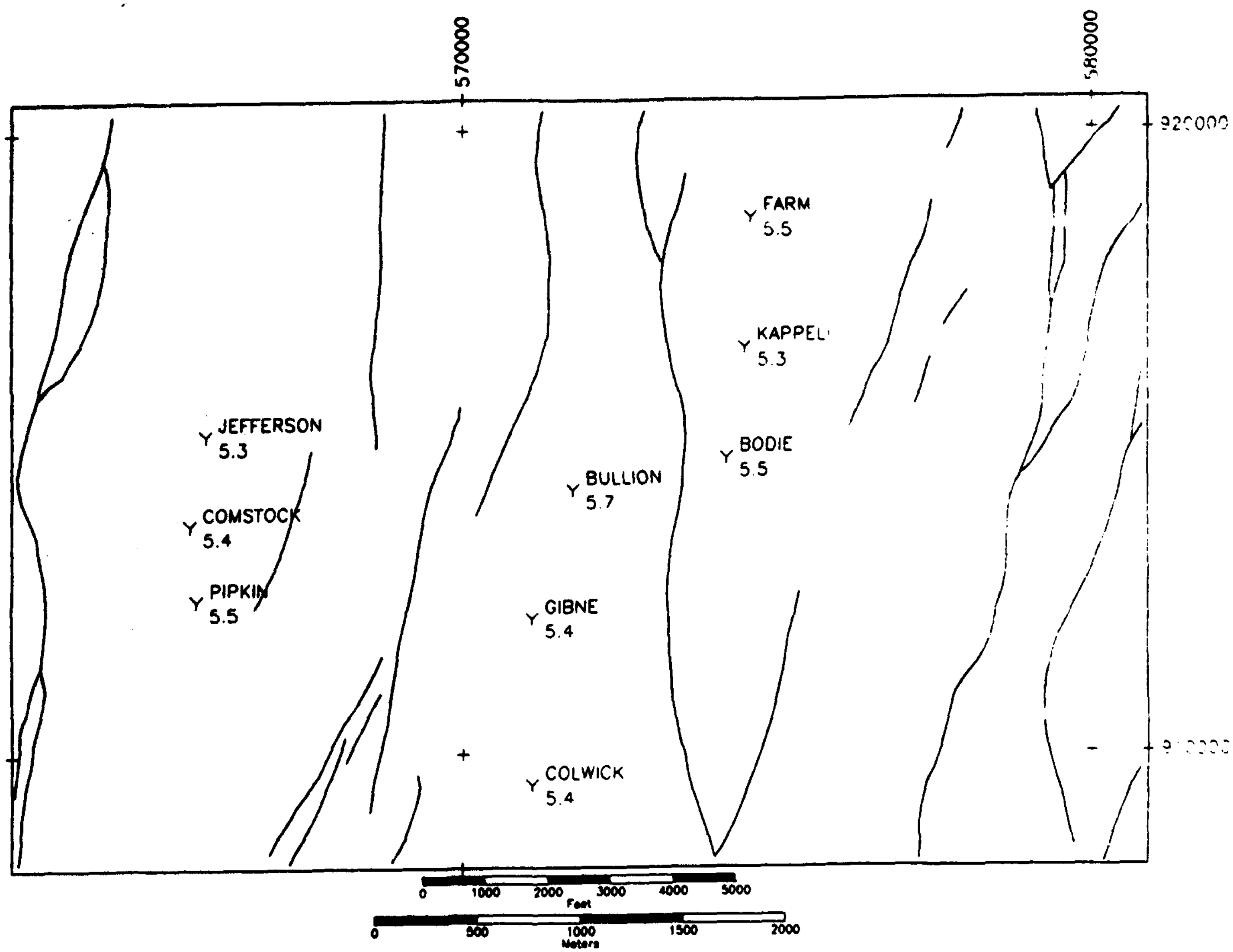

Figure 4. Locations of previously detonated explosions near BULLION. The body wave magnitude is shown as a rough measure of explosion size.

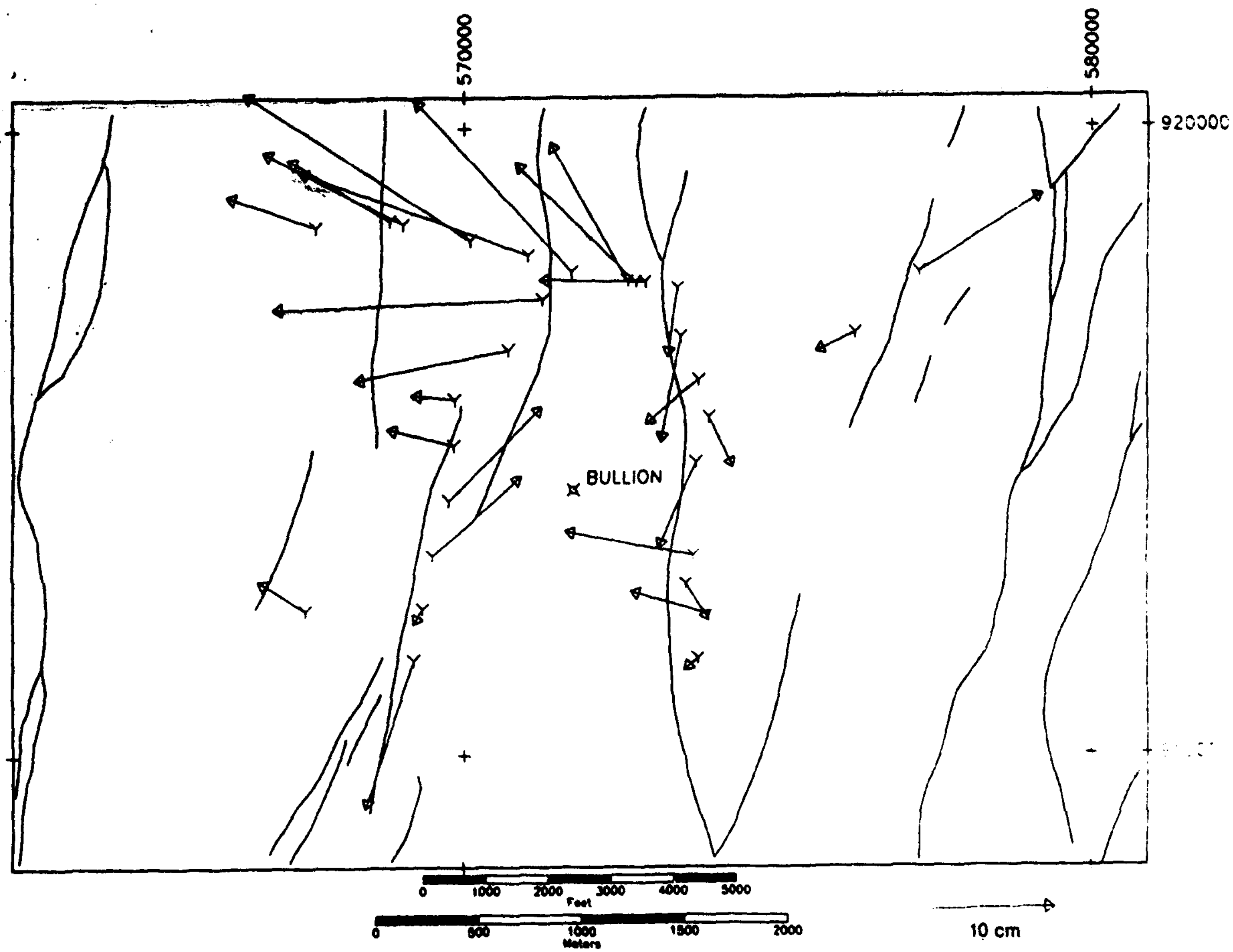

Figure 5. Horizontal displacements due to the explosion BULLION.
A 10 cm vector is displayed at the bottom for scale.

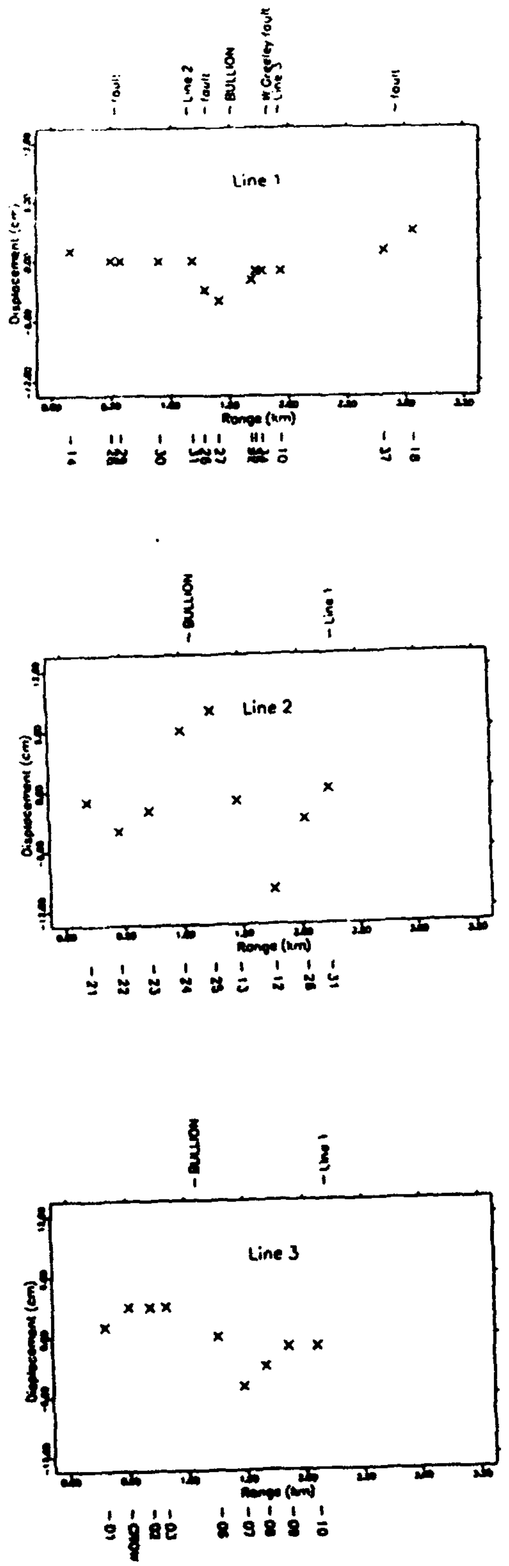

Figure 6. Vertical displacements due to the explosion BULLION on profile lines 1, 2 and 3, which are locąted on Figure 3.

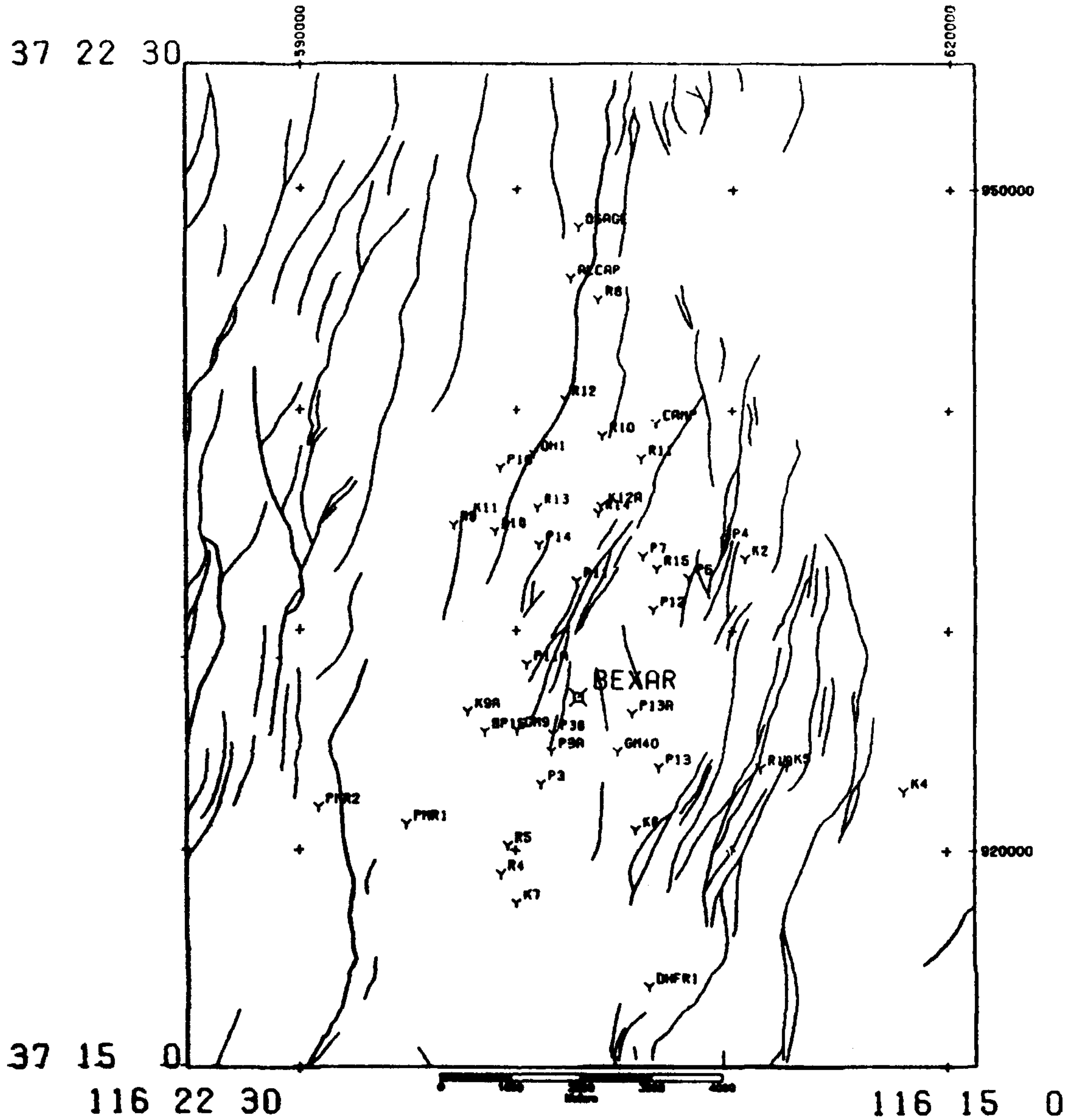

Figure 7. The network of monuments established for the BEXAR survey. Faults which have been mapped in the vicinity are also shown on the figure.

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